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Spectrum and chemical composition of the remarkable planetary nebula NGC 6537

(gaseous nebulae/stellar evolution/nucleogenesis)

WALTER FEIBELMAN*, LAWRENCE H. ALLER†, C. D. KEYES†, AND S. J. CZYZAK‡

*National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, MD 20771; †University of California, Los Angeles, CA 90024; and ‡Ohio State University, Columbus, OH 43210

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ABSTRACT Observations with the image tube scanner at the Shane 3-m telescope are combined with data obtained with the International Ultraviolet Explorer to assess the spectrum of the remarkable high-excitation planetary nebula NGC 6537. We have analyzed the spectrum of this nitrogen-rich object with the aid of the theoretical nebular models. The models permit one to estimate the fraction of unobservable ions of abundant elements. On the scale log N(H) = 12, the logarithmic abundance values for He, C, N, and O are as follows:

	He	C	N	O
NGC 6537	11.27	7.6	8.95	8.23
Sun	11.0	8.66	7.98	8.91

The abundances of Ne S, Cl, and Ar appear to be essentially solar to within a factor of 2. Our interpretation is that the progenitor of NGC 6537 had a chemical composition not differing greatly from that of the Sun. In the course of its prenebular evolution, C and probably O were converted to N and much H was converted to helium.

The planetary nebula NGC 6537 (10 + 0°1) appears to be an irregular bipolar object. Its remarkably complex structure is well illustrated in Minkowski's photograph (1) or in the isophotic contours derived therefrom (2). Table 1 summarizes some of the relevant data. We give the rf position as measured with the Very Large Array or VLA (3). The bright central region is only a few arc seconds in diameter (4, 5) but fainter extensions reveal a much larger object (1, 2). The nebula is heavily reddened by interstellar smog. The measured flux at Hβ (6, 7) is dimmed by 20 decibels (dB) [refs. 5, 8, and 9]. This circumstance makes observations in the UV difficult. Estimates of the distance of NGC 6537 based on the assumption that the nebula is optically thin lead to large values (5, 6), whereas those that are based on more plausible hypotheses (8, 10, 11) lead to smaller and seemingly more realistic distances. We emphasize that uncertainties in distances are among the most severe handicaps encountered in studies of planetary nebulae.

A number of observers (3, 5, 12, 13) have made rf observations of NGC 6537. Combinations of these flux data with optical measurements probably give the best determination of interstellar extinction.

Spectrum

NGC 6537 is an example of a helim- and nitrogen-rich planetary of Peimbert's composition type I (14). In that respect it is similar to NGC 2440 (15–17) and NGC 6302 (18, 19), which are two of the most outstanding objects of this type. The N/H ratio seems to be extreme, as is indicated by the great strength of the [N II] lines compared to Hα (20).

Photoelectric measurements at Mt. Wilson in 1966 yielded a 5007/4959/Hβ ratio of 993/338/100, whereas photographic observations secured with a prime focus spectrograph at Lick Observatory indicated an excitation class (2) of 9 or 10. Measurements of the weaker lines seem to be too strong. We used the photographic measurements here only to get the 3726/3729 [O II] ratio.

We employed conventional procedures to observe the spectrum of NGC 6537 with the image dissector scanner at the Lick 3-m telescope, using both red- and green-sensitive tubes in order to cover the spectrum from the practical UV limit near λ3300 Å to the near-infrared limit near λ8600 Å. Observations of suitable comparison stars permitted determination of the instrumental responses function, while corrections for atmospheric extinction were obtained from standard determinations carried out for Lick Observatory.

Observations with the International Ultraviolet Explorer (IUE) were obtained October 23, 1984. We employed a 210-min exposure, being limited by the radiation background. Because of the attenuation produced by interstellar particles amounting to 43 dB at the C III λ1909 line and 51 dB at the extreme edge of the range of N V λ1240, signals from important lines often were weak.

Determination of the interstellar extinction may be made by a number of procedures: comparison of Hβ and rf fluxes, the Balmer decrement in H, the Paschen–Balmer ratio in He II, the diffuse 2160 Å absorption feature, and certain ratios of collisionally excited lines. (For a compilation, see pp. 187–193 of ref. 21.) In NGC 6537, the λ2160 Å method cannot be used because the nebular continuum was not observed. A value of C = 1.95 appeared to fit best both the optical and UV data. To correct observed fluxes for interstellar extinction we used Seaton's data (22).

Table 2 gives the relative intensities of observed lines as normalized to I(Hβ) = 100 and corrected for interstellar extinction with C = 1.95. Line intensities at the UV end of the range, especially λ3340, are uncertain because of effects of atmospheric and interstellar extinction. The response function is unreliable in the region of the Paschen lines. All lines whose intensities are followed by a colon are uncertain and may be in error by ±60%. Generally, lines stronger than 10 have errors of ≈5–10%. Lines between 1 and 10 may have errors of the order of 15–25%, whereas those weaker than 1 may be in error 30–50%.

Table 3 gives the UV line fluxes measured with the IUE. The first two columns give the wavelength and identifications (as in Table 2). Column 3 gives the observed flux in units of 10^{-14} ergs·cm^{-2}·sec^{-1}. Column 4 gives I_c corrected for interstellar extinction. The N V λ1240 intensity is very uncertain. We rejected it in our final derivation of the nitrogen abundance.

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Abbreviations: IUE, International Ultraviolet Explorer; VLA, Very Large Array; ICF, ionization correction factor; dB, decibel(s).

Table 1. Basic data for NGC 6537

Position α = 18 hr 02 min 15.19 sec)	
	) (1950) (ref. 3)
δ = 19° 50′ 51.0″)	
Angular diameter 5″ (ref. 4), 7.4″ (ref. 5) bright central region only	
Logarithm of Hβ flux in ergs·cm^{-2}·sec^{-1}	
log F(Hβ) = −11.78 (ref. 6)	
−11.66 (ref. 7)	
Extinction constant C = log F_c(Hβ)/F(Hβ), where F_c(Hβ) is the flux corrected for interstellar extinction C = 1.47 $E(B - V)$, where $E(B - V)$ is the color excess.	
	C = 1.79 (ref. 5); = 2.00 (ref. 8); = 2.09 (ref. 9)
Distance in kiloparsecs (1 parsec = 3.09 × 10^{16} m)	
	4.33 (ref. 6); 1.20 (ref. 8); 2.95 (ref. 5); 1.24 (ref. 10); 0.652 (ref. 11)
rf observations: flux in janskys (1 jansky = 10^{-26} W·m^{-2}·Hz^{-1})	
	2.7 GHz: 0.37 ± 0.06 (ref. 12)
	5 GHz: 0.671 (ref. 5)
	6 GHz: 0.574 (ref. 3)
	14.7 GHz: 0.126 (ref. 13)
	20 GHz: 0.383 (ref. 3)

Plasma Diagnostics and Ionic Concentrations

Relative intensities of collisionally excited lines yield estimates of the electron density N_ε and electron temperature T_ε in the radiating layers. Various writers (1, 21, 23, 24) have described the procedures. In view of the extremely filamentary character of this object, it is not surprising that different criteria give differing values. The [O II] nebular line 3726/3729 ratio gives a lower density than does the ratio of the nebular to auroral lines. Some of this discordance may be attributed to photometric limitations in the older photographic material and to the large baseline between the 3727 and 7319, 30 features. The [S II] line ratio indicates $N_\varepsilon \approx 10^4$. For this density the [N II] and [O III] lines give T_ε = 16,500 and 15,400, respectively, again a possible effect of the lines arising from different strata. For the present calculations we

Table 2. Optical region spectrum of NGC 6537 (10 + 0°1)

λ, Å	Identification	I_c	λ, Å	Identification	I_c	I_λ, Å	Identification	I_c
3340.8	[Ne V]	180:	4649	C III, O II	0.49	6363.8	[OI]	2.76
3428.6	[Ne V]	501	4658	C IV, [Fe III]	0.63	6406.5	He II	0.58
3444	O III	20	4685.8	He II	98.5	6435.1	[Ar V]	5.6
3726.0	[O II]	14.2	4711	He I, [Ar IV]	14.5	6548.1	[N II]	129
3728.7	[O II]	8.5	4725	[Ne IV]	1.6:	6563	Hα	274
3734.3	H 13	2.3	4740.2	[Ar IV]	18.7	6584.4	[N II]	363
3750.1	H 12	3.6	4871	Hβ	100	6678.2	Hu I	3.24
3734.6	O III	(1.8)	4959.0	[O III]	361	6716.5	[S II]	4.5
3759.8	O IV	6.3	5007.9	[O III]	1010	6730.7	[S II]	9.0
3770.6	H II	3.7	5200	[N I]	2.2	6891.8	He II	0.7
3797.8	H 10	5.1	5411.5	He I	7.7	7005.7	[Ar V]	13.0
3819.6	He II	3.0	5517.7	[Cl IV]	0.54	7065.3	He I	6.7
3835.4	H 9	7.0	5537.8	[Cl IV]	1.10	7135.8	[Ar III]	34.1
3868.8	[Ne III]	110	5577.4	[O I]	0.37	7170/79	[Ar IV, He II]	1.5
3889	H 8, He I	15.1	5592.2	O III	0.20	7237.5	[Ar IV]	0.93
3967.5	[Ne III]	45.6	5608	[K VI]	0.20	7262.8	[Ar IV]	0.91
3970.0	Hε		5721.1	[Fe VII]	0.30	7281.3	He I	0.68
4026	He I, He II	2.3	5754.6	[N II]	18.5	7319.9	[O II]	8.4
4068.6	[S II]	10.8	5875.6	He I	13.2	7330.2	[O II]	6.7
4076.2	[S II]	2.9	5913.5	He II	0.2	7530.5	[Cl IV]	1.0
4101.7	Hδ	25.4	5932.2	He II	0.2:			
4120.7	He I	0.89	5953	He II	0.2:	7587	He II	1.3
4199.8	He II	1.8	5977	He II	0.2:	7751.1	[Ar III]	8.1
4267.3	C II	0.30	6006	He II	0.2:	8045.6	[Cl IV]	2.3
4340.6	Hγ	43.4	6037	He II	0.3	8236.6	He II	2.0
4351:		0.88	6074	He II	0.3	8359	H P22	0.1:
4363.2	O III	21.4	6087	He II	0.4:	8374	H P23	0.1:
4387.8	He I	0.51	6101.8	[K IV]	0.82	8392.4	H P20	0.2:
4471.4	He I	3.76	6121		0.3	8413.2	H P19	0.2:
4541.4	He II	2.87	6171	He II	0.5:	8438	H P18	0.3:
4608	[Fe III]	1.3	6234	He II	0.61	8467.3	H P17	0.3::
4630		0.9	6300.3	[O I]	7.5	8502.5	H P16	0.4:
4634.1	N III	3.0	6312.1	[S III]	6.9	8545.5	H P15	0.4:
4640.7	N III	5.8	6347	Si II	0.29	8577	[Cl II]	0.5:
						8598	HP 14	0.6:

All lines whose intensities are followed by a ":" are uncertain and may be in error by ±60%.

Table 3. UV fluxes

λ, Å	Identification	F(−14)	I_c
1240	N V	9.4:	6150:
1404	O IV, Si IV	2.17	332
1485	N IV	8.48	720
1549	C IV	8.30	895
1640	He II	8.47:	640
1661	O III	2.63:	192:
1750	N III	12.76	960
1909	C III	2.51	246

Estimates of errors are difficult to give because of attenuation by the interstellar medium. The stronger lines may have uncertainties ranging from 15% to 30%. The weaker lines may be in error by 40%. Those identified by a ":" are subject to even larger errors and have not been used in abundance estimates.

adopted N_ε = 10,000 electrons·cm^{-3} and T_ε = 16,000 K, although some of the model calculations, cited below, suggested a lower density might be a happier choice. For ions of the p^2 and p^4 configurations, a change in the electron density from 3000 to 10,000 electrons per cm^3 will have little effect. For p^3 ions, an uncertainty in N_ε can produce somewhat larger effects. Errors in T_ε are specially serious for ions with higher excitation potentials such as [Ne V], C III, C IV, N III, and N IV. The concentrations of He^+ and He^{2+} lines are calculated from the recombination lines of He I and He II.

Table 4 summarizes our calculation of ionic concentrations from the observed line intensities. Column 1 gives the relevant ionization stage. (Note λ4267 C II is listed under C III. This intensity of this line treated as a recombination feature measures the concentration of C^{2+} or C III ions.) Column 2 gives the wavelength of the relevant, collisionally excited (except for 4267) lines. Column 3 gives the line intensity on the scale $I(H\beta)$ = 100; column 4 gives the adopted value of Seaton's (23) parameter $t = T_\varepsilon/10{,}000$. For UV lines of highly excited ions we have used theoretical models to estimate T_ε. Column 5 gives values of the coefficient $C_{\lambda,i}(x, t)$ in:

$$\frac{N(X_i)}{N(H^+)} = C_{\lambda,i}(x, t)\,\frac{I(\lambda_i)}{I(H\beta)},$$

where $I(\lambda_i)$ is the intensity of the line of ion, i, of wavelength λ. Seaton's parameter (23) $x = 10^{-2} N_\varepsilon/\sqrt{T_\varepsilon}$. We have taken values of $C_{\lambda,i}(x, t)$ from chapter 5 of ref. 21.

Table 4. Ionic concentrations

Ion	λ, Å	I	t	$C_{\lambda,i}(x, t)$	$N(X_i)$
C III	4267	0.3	1.6	0.116	3.49 (−9)
C III	1909	246	1.6	5.45 (−6)	1.35 (−5)
C IV	1549	895	1.87	1.18 (−6)	1.05 (−5)
N II	6584	363	1.6	7.64 (−6)	2.77 (−5)
N III	1750	960	1.60	5.18 (−5)	4.97 (−4)
N IV	1485	720	1.90	1.76 (−5)	1.27 (−4)
N V	1240	6150:	2.18	4.54 (−6)	2.79 (−4):
O II	3727	22.7	1.6	2.41 (−5)	5.54 (−6)
O III	4959, 5007	1371	1.6	6.90 (−5)	9.46 (−5)
O III	1663	192:	1.53	1.64 (−4)	3.15 (−4):
Ne III	3868	110	1.6	2.62 (−5)	2.89 (−5)
Ne IV	4725	1.16	1.96	6.52 (−4)	1.09 (−5)
Ne V	3341, 3426	681	2.16	6.73 (−6)	4.58 (−5)
S II	6717/30	13.5	1.6	3.38 (−6)	4.56 (−7)
S III	6312	6.9	1.6	4.54 (−5)	3.14 (−6)
Cl III	5517/37	1.64	1.6	2.78 (−6)	4.56 (−8)
Cl IV	7530/8045	3.3	1.6	2.28 (−6)	7.47 (−8)
Ar III	7135	34.1	1.6	3.17 (−6)	1.08 (−6)
Ar IV	4740	18.7	1.6	1.06 (−5)	1.98 (−6)
Ar V	6435/7005	18.6	1.7	3.47 (−6)	6.46 (−7)

Theoretical Models and the Determination of the Nebular Chemical Composition

The last column of Table 4 gives us the ionic concentrations. For weaker lines such as those of [Cl IV] the chief source of uncertainty lies in the measured intensities, whereas for the stronger lines of the p^2 and p^4 configurations, uncertainties in T_ε play a role. Data from lines such as [Ne IV] λ4727 are affected by both T_ε uncertainties and observational errors.

For many elements, the greatest uncertainty to obtaining elemental abundances lies in allowing for unobserved ionization stages. Nitrogen is one of the most popular examples. A favorite procedure is to assume $N^+/N = O^+/O$, where $n(O)/n(H^+) = [n(O^+) + n(O^{2+})]/n(H^+)$, which seems to give results accurate to within a factor of about 2 in nebulae showing a large range of excitation (20, 25–27). For low-to-moderate excitation objects, somewhat similar types of formulae have been developed for other ions, most notably neon, but for other ions such as sulfur, chlorine, and argon, such nonphysical, *ad hoc* formulae often prove frustrating.

The most rigorous approach is to calculate a theoretical nebular model in which one reproduces the observed line intensities. The most successful model of this type appears to have been achieved for NCG 7662 (28). Here one deals with a relatively symmetrical object, not heavily obscured by interstellar smog and for which a wealth of good observational data is available.

For an irregular object such as NGC 6537, one can scarcely expect a theoretical model based on spherical symmetry to yield precise agreement with observations. Instead, the best one can hope for is that the theoretical model will serve as an interpolation device (15, 29). We try to reproduce the general level of excitation, notably the He II/He I 4686/4861, [O II]/O III] λ3727/5007, and [Ne III]/[Ne V] 3868/3426 line ratios. The model should also give an electron temperature in harmony with the observed value. It is not possible to reproduce the detailed line intensities. When the critical line ratios and general level of excitation are accounted for, we then use the model to obtain the fraction of ions of a given element that is in unobservable stages of ionization. Thus, we obtain the ionization correction factors (ICFs).

One difficulty is that one has a sufficient number of adjustable parameters to preclude the isolation of a unique model. These include the radius of the star, the effective temperature of the star, or, more particularly, the flux distribution of the emergent radiation from its surface, the density of the gas, its chemical composition, and finally the geometry. For obvious computational reasons, we are restricted to symmetrical models. These may be spheres of uniform density, dense shells surrounding a low-density inner zone, or composite models with a shell consisting of both high- and low-density segments (ref. 30; see also, chapter 7 of ref. 21).

For a given emergent stellar flux, considerable differences in the predicted spectrum are found depending on whether we assume a uniform sphere or shells with various ratios of shell thickness to radius (31). We have tried a variety of models, several with a uniform sphere and several with shells of varying density and shell thickness. It soon became apparent that a very high central star temperature was required. We employed initially a blackbody with T_{eff} = 180,000 K. The predicted intensity of [Ne V] was too low; that of He II λ4686 was too high, even for the uniform sphere model. Accordingly, we tried UV excesses in the region beyond 100 eV or λ <127 Å, but no alterations in the flux seemed capable of reproducing the strong [Ne V] lines. At the present time, we suspect that these lines, which are severely affected by both terrestrial atmospheric extinction and interstellar extinction, may have faulty intensities. We also tried an absorption at the He II ionization limit to reduce the He II/He I ratio. Shell models with radii 0.075 and 0.10

Table 5. Chemical composition of NGC 6537

						log N			
Element	ΣN (X_i)*	ICF (4)†	N (4)‡	ICF (5S)§	N (5S)¶	Model 4	Model 5S	Mean PN‖	Sun**
Helium	0.187	1.00	0.187		0.187	11.27	11.27	11.04	
Carbon	2.40 (−5)	1.71	4.1 (−5)	1.51	3.6 (−5)	7.61	7.56	8.89	8.66
Nitrogen	6.52 (−5)	1.39	9.1 (−4)	1.33	8.7 (−4)	8.96	8.94	8.26	7.98
Oxygen	1.00 (−4)	1.75	1.75 (−4)	1.56	1.56 (−4)	8.24	8.19	8.64	8.91
Neon	8.51 (−5)	1.15	9.8 (−5)	1.13	9.6 (−4)	7.99	7.98	8.03	8.05
Sulfur	3.59 (−6)	4.65	1.67 (−5)	3.75	1.35 (−5)	7.22	7.13	7.00	7.23
Chlorine	1.203 (−7)	2.39	2.88 (−7)	2.0	2.40 (−7)	5.46	5.38	5.22	5.5
Argon	3.71 (−6)	1.66	6.17 (−6)	1.44	5.34 (−6)	6.79	6.73	6.43	6.57

In the calculation of the oxygen abundance we did not use the O III λ1661 line because of the large uncertainty in its intensity.
*The total number of ions of each element.
†The ICF for uniform sphere model 4.
‡N (element) for model 4.
§The ICF for shell model 5S.
¶N (element) for model 5S.
‖"Mean" composition of a planetary nebula (29).
**Solar composition (see text).

parsec and various shell densities showed promise but it was impossible to represent accurately the observed intensities.

Lack of space prevents our making a detailed comparison of observed intensities with predictions of the various models. Table 5 presents results obtained with the best uniform sphere model we obtained, model 4, and with a shell model, 5S. Table 6 summarizes some characteristics of the models. Model 4 follows a blackbody distribution longward of 125 Å, while model 5S has a dip at the helium ionization edge.

The data in the first three columns of Table 4 are used to calculate in column 2 of Table 5 the sum of the observed ionic concentrations. Notice that for carbon we do not use the results from λ4267. Further, we have not used the N V λ1240 results because they are subject to large uncertainties. We make two estimates, columns 4 and 6, of the chemical composition of NGC 6537, in one instance deriving the ICFs from model 4 (column 3) and in the other from the shell model 5S (column 5). Columns 7 and 8 compare log N derived from the homogeneous sphere and shell models. In spite of the differing energy distributions on the high-frequency side of the He II limit and the different geometries, the two sets of abundance estimates fail to agree by less than one dex. The usual procedure of comparing abundances employed in the model with those found from ionic concentrations and ICF factors is not very meaningful here as the models serve here really only to provide a basis for estimating the role of the missing ionization stages.

Discussion

The helium abundance is not dependent on the models. We obtained the $N(He^+)/N(H^+)$ ratio of 0.100 from the recombination He I lines λ5876, 4471, and 6678. The He II lines λ4686, 5411, and 4541 gave $N(He^{2+})/N(H^+) = 0.087$. Then $N(He/N(H) = 0.187$, which makes NGC 6537 a distinctive He-rich object.

We may take a mean of data in columns 4 and 6 of Table 5 as indicative of the chemical composition of NGC 6537. For comparison, column 9 gives the composition of an "average" planetary (29), whereas column 10 gives solar abundances from a recent compilation (32). Helium is almost twice as abundant as in an average planetary or the interstellar medium. No good solar data are available. Carbon is more abundant in the average planetary than in the Sun but is less abundant in NGC 6537 by an order of magnitude! On the other hand, nitrogen is about an order of magnitude more abundant in NGC 6537 than in the Sun, while in a "normal" planetary it is only about twice as abundant. Note that oxygen is severely depleted as compared with *either* the average planetary or the Sun. For neon, sulfur, chlorine, and argon, the differences between the three groups of objects are much reduced, particularly when we recall that the solar abundances of neon, chlorine, and argon are poorly established.

Thus, it would seem that for neon and observable heavier elements, NGC 6537, the average planetary, and the Sun have essentially the same chemical composition. It is when we come to lighter elements involved in the carbon–nitrogen cycle and helium burning that the differences become engaging. Most planetaries show enhanced carbon and some show enhanced nitrogen with respect to the Sun (14, 21, 33). NGC 6537 resembles NGC 6302 (18) in showing a depletion of carbon and an enhancement of nitrogen, but NGC 6302 has about the same O abundance as the average planetary. The depletion of carbon is more severe. Thus, NGC 6537 appears to be a unique object in whose progenitor star the carbon–nitrogen and related cycles ran very efficiently converting not only carbon into nitrogen but evidently cutting into the oxygen supply as well. Thus, $p + {}^{16}O \rightarrow {}^{17}O$; $p + {}^{17}O \rightarrow {}^{14}N + \alpha$, but a temperature of 30,000,000 or more would be need-

Table 6. Some characteristics of nebular models

Characteristic	Model 4: uniform sphere	Model 5: virtually hollow shell
Stellar flux distribution	Blackbody T = 180,000 K for λ >125 Å Strong UV excess	Blackbody T = 180,000 K for λ >228 Å, then a dip at He II limit with a smooth UV distribution and excess at λ <157 Å
Density	N_H = 10,000 cm^{-3} throughout	N_H = 10,000 cm^{-3} in shell = 10 cm^{-3} in interior
Inner radius	0	0.075 parsec
Outer radius	0.0972 parsec	0.1095 parsec
Strömgren sphere radius	0.0991 parsec	0.1110 parsec
τ_H at outer radius	35	75
$T\varepsilon$	15,250	16,388

ed in the H burning zone. Hence, a progenitor somewhat more massive than for an ordinary planetary is needed. The sum of the masses of C, N, and O in NGC 6537 differs from the corresponding solar value by about 25%, strongly suggesting that an original solar abundance pattern was modified by nuclear reactions. Further observations of these interesting objects are strongly urged.

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